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Planar Plasmonic Terahertz Waveguides for Sensor Applications

Maidul Islam, Dibakar Roy Chowdhury, Gagan Kumar

Abstract**—**We investigate sensing capabilities of a planar plasmonic THz waveguide. The waveguide is comprised of one dimensional array of periodically arranged sub wavelength scale corrugations in the form of rectangular dimples in order to ensure the plasmonic response. The THz waveguide transmission is observed for polyimide (as thin film) substance filling the dimples. The refractive index of the polyimide film is varied to examine various sensing parameters such as frequency shift, sensitivity and Figure of Merit (FoM) of the fundamental plasmonic resonance supported by the waveguide. In efforts to improve sensing characteristics, we also examine sensing capabilities of a plasmonic waveguide having V shaped corrugations and compare results with that of rectangular dimples. The proposed study could be significant in developing new terahertz sensors with improved sensitivity utilizing the plasmonic waveguides.

Keywords**—**Terahertz, plasmonic, sensor, sub-wavelength structures.

I. Introduction

THERE has been a considerable interest in developing a guided wave devices owing to their significance in building a network or communication system. Efficient waveguides offering low loss and high confinement factors are crucial to several applications viz. slow light devices [1], [2], band pass and band stop filter [3], [4], sensors [5]-[7], etc. At the core of THz frequencies (0.1-3 THz), several wave guiding schemes have been exercised to transfer terahertz waves exhibiting low loss and high confinement of the modes aiming applications in diversified areas [8]-[10]. For instance, Cao and Nahata have proposed a cylindrical metal wire waveguide by utilizing milled grooves directly into the metal wire and showed that the radially polarized coupled THz surface waves propagates onto the metal wire waveguide [11]. Chen and Chen have investigated polymer tube based THz waveguide [12] and showed that the waveguide has better wave guiding characteristics such as loss, confinement and mode area compared to the solid polymer fiber. Recently, Chen et al. proposed a parallel plate waveguide with a single adjustable air gap which to demonstrate a tunable multi-band THz notch filter [13]. The modulation [14], [15], slow light systems [16], [17], band pass filter [18], etc. are few other applications that have been recently reported using the approach of THz waveguides.

M. Islam and G. Kumar are with the Department of Physics, Indian Institute of Technology Guwahati, Guwahati– 781039, Assam, India (e-mail: gk@iitg.ernet.in).

A. Ahmad is with the College of Information Technology, United Arab Emirates University, Al Ain, UAE.

D. R. Chowdhury is with Mahindra \'Ecole Centrale, Jeedimetla, Hyderabad 500043, Telangana, India (e-mail: dibakarrc@gmail.com).

The THz waveguides have also been investigated recently using the concept of spoof plasmons in conducting media. In this context, several plasmonic waveguides have been demonstrated with promising applications in slow light devices [19], high speed communication [20], filters [21], [22] etc. Williams et al. have investigated highly confined guiding of THz modes in a plasmonic metamaterials waveguide consisting of metal surface decorated with two dimensional array of subwavelength periodic pits [23]. Subsequently, THz waveguides and passive devices such as Y-splitters [24], 3 dB couplers [25] are demonstrated with the ability of propagating THz modes to tens of centimeters on a planar plasmonic surface. Recently 3D printing techniques [26] have been used to create plasmonic THz waveguides. While replacing metals with the semiconductors, Kumar et al. have experimentally demonstrated the guiding of THz modes in a waveguide comprising of subwavelength scale pillars in a highly doped silicon surface [27]. Several other plasmonic waveguides with its constituents including tilted pillars [28], slanted grooves [29], V-grooves [30] have been examined in recent times. The potential of plasmonic waveguides in actualizing THz devices has also been rigorously persuaded. Nagai et al. designed a parallel metal plate waveguide with periodic array of pillars at its metal plates and examined an achromatic quarter wave plate for THz applications [31]. Very Recently, Mittendorff et al. proposed a graphene based waveguide for THz modulation [32]. In their work, the graphene sheets are perforated in dielectric waveguide to tune the absorption of THz and hence to modulate it. The THz plasmonic waveguides offer strong confinement of the electric field within the grooves as well as on the surface and therefore, could be important in sensing analyte with greater sensitivity when the analyte is filled in the grooves. Therefore, rigorous efforts are required to explore the potential of THz plasmonic waveguides in sensors.

In this paper, we examine the sensing capabilities of the fundamental resonant mode supported by the plasmonic waveguide comprising of rectangular corrugations compare the results with that of V-grooves constituting the plasmonic waveguide. We have organized the paper as follows: first, we examine the frequency domain waveguide transmission spectra of the fundamental modes supported by the plasmonic waveguide comprising of rectangular grooves filled with different refractive indices of the polyimide to establish the sensing capability of the plasmonic waveguide. After that, we discuss various sensing parameters, viz. frequency shift versus refractive index, the sensitivity and the Figure of Merit (FoM) of the fundamental mode in case of rectangular grooves and

V-grooves and discuss results in detail. Finally, we summarize results in the conclusion section.

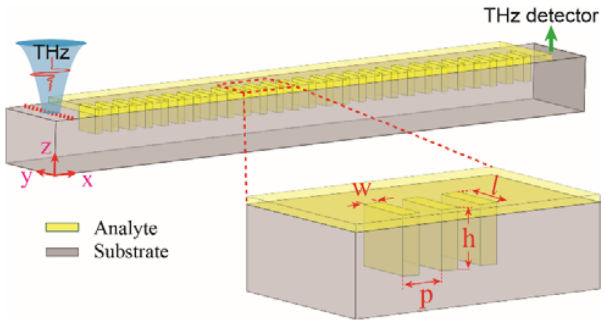

Fig. 1 Schematic of a planar plasmonic THz waveguide; 3-Dimensional view of the waveguide comprising one dimensional array of periodic corrugations: The parameters ‘l’, ‘w’, ‘h’ and ‘p’ represent the length, width, depth and periodicity of the structure. The analyte is present in the rectangular dimples as well as on the substrate

II. The Schematic of THz Plasmonic Waveguide Sensors

The schematic of the proposed plasmonic waveguide geometry is shown in Fig. 1. The waveguide geometry is composed of a metallic substrate having periodically arranged one dimensional array of rectangular grooves. The top surface of the waveguide along with the grooves is filled with the polyimide. The grey and yellow colors in the schematic indicate the metal substrate and the polyimide, respectively. The grooves parameters are given as: length (l) = 0.5 mm, width (w) = 0.2 mm, depth (h) = 0.5 mm. The thickness of metal substrate ‘d’ is 0.8 mm and periodicity, ‘p’ = 0.4 mm. The periodicity of the substrate is assumed to be fixed throughout our study. The total length of the waveguide is considered to be 30 mm. In our numerical simulations, the waveguide is excited with a discrete source of single cycle THz waveform at one end of the waveguide. The signal once coupled to the corrugated structures, propagates along the designed one-dimensional waveguide and finally detected at the other end. The detected time domain signal is converted into the frequency domain spectra using Fast Fourier Transform (FFT). The numerical simulations are performed using finite element time domain solver of the CST Microwave Studio simulation software.

III. Sensing Analyte in Plasmonic Waveguide

In order to investigate sensing capabilities of the proposed plasmonic waveguide, we used the technique of frequency shift of the fundamental mode of the waveguide transmission w.r.t. the change in the refractive index of the polyimide. More specifically, we focused on a change in the anti-resonant frequency of the modes when grooves are filled with analyte w.r.t. the intrinsic anti-resonant frequencies (i.e. without any analyte). It may be noted that the anti-resonant frequencies are quite significant in plasmonic waveguides as they occur from interference of discrete spectrum and continuum spectrum. First, we study waveguide transmission spectra of the plasmonic waveguide having rectangular grooves without any analyte. The corresponding frequency domain spectrum is reflected by the red trace for ‘n’ = 1 in Fig. 2. Subsequently, the polyimide substance of different refractive index is filled in the grooves and corresponding waveguide transmission is calculated. One may use the technique of spin coating or drop casting for depositing analyte into the grooves as well as onto the surface. In the waveguide transmission spectra, a shift in the anti-resonant frequency is observed as grooves are filled with analyte. For ‘n’ =1, the anti-resonant frequency is found to appear at 0.3 THz, however it shifts to 0.17 THz when analyte refractive index is ‘n’ = 2. For our study, we varied refractive index as ‘n’ = 1, 1.2, 1.4, 1.6, 1.8, and 2.0 and observed a red shift in the anti-resonance frequency of the fundamental mode. Clearly, the shift in frequency is observed because of an interaction between the highly confined electric field of the mode at the surface and the analyte present there.

IV. Sensing Characteristics of Rectangular Grooves and V-Grooves: A Comparison

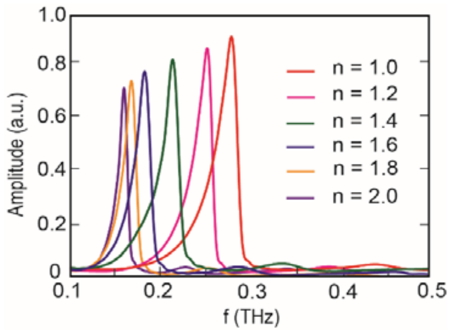

Fig. 2 Numerically simulated frequency domain terahertz waveguide transmission for the plasmonic waveguides having rectangular dimples filled with refractive indices of i.e. ‘n’ = 1, 1.2, 1.4, 1.6, 1.8, and 2

In order to comprehensively analyze the sensing characteristics of the proposed plasmonic waveguide, we further examine frequency shift w.r.t. the refractive index, the sensitivity and the FoM of the fundamental mode supported by the waveguide comprising rectangular grooves. Since the shape and size of the corrugations are crucial to determine the confinement of a mode to the surface, therefore in effort to improve the sensing characteristics, we examine plasmonic waveguide comprising V-grooves of same width and depth. The sensing characteristics of V-grooves are compared to that of the rectangular grooves. The V-grooves are chosen to improve sensing features since they are promising in resulting strong confinement of the modes at the metal-air interface [30]. The strong confinement to the surface in highly desirable for sensing applications as the analyte at the surface extensively interacts with the wave of the order of several wavelengths.

In Fig. 3, we plot frequency shift of the fundamental mode versus refractive index of the polyimide filling the rectangular grooves of the plasmonic waveguide. For comparison, the frequency shift response for the same amount of analyte i.e.

0.025 mm^3 in case of V-groove is also plotted in the same figure. The blue and red traces in the figure correspond to rectangular grooves and V-grooves, respectively. We varied refractive index ('n') as = 1, 1.2, 1.4, 1.6, 1.8, and 2 to determine the frequency shift. As the refractive index is increased, we observe a linear shift in the anti-resonant frequency of the fundamental mode. The shift is more prominent in case of V-grooves, indicating better sensing characteristics of the V-grooves compared to the rectangular grooves.

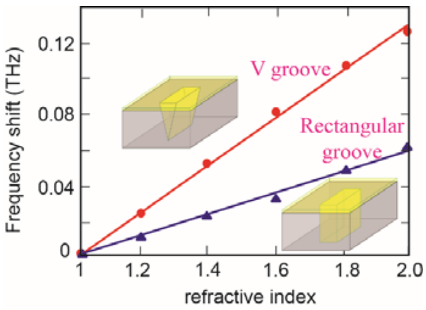

Fig. 3 The variation of frequency shift of the fundamental mode versus refractive index of the polyimide substance for the two plasmonic terahertz waveguide. The red line corresponds to the plasmonic waveguide having V-grooves, however blue line represents the case of rectangular grooves filled with refractive indices of i.e. '*n*' = 1, 1.2, 1.4, 1.6, 1.8, and 2

For comprehensive understanding of the sensing parameters, next we examined sensitivities of the fundamental mode for the plasmonic waveguides with rectangular grooves and V-grooves w.r.t. the increasing quantity of polyimide substance. In order to do so, we varied the refractive index of analyte as 'n' = 1, 1.2, 1.4, 1.6, 1.8, and 2 for each of the quantity. The frequency shift, i.e. Δf is plotted versus refractive index to obtain the sensitivity of the mode corresponding to a certain quantity of analyte using $\Delta f / \Delta n$. The response of sensitivity versus analyte quantity (ΔV) is plotted in Fig. 4 (a). It may be noted that as the volume of the analyte increases, the sensitivity also monotonically increases. For the same quantity of analyte, the sensitivity is about five times higher for the V-grooves compared to the rectangular grooves. For instance, for analyte quantity, $\Delta V \sim 0.018$ mm^3, the sensitivity of fundamental mode in V-grooves turns out to be ~ 0.11 THz / R.I, however it is ~ 0.02 THz / R.I in case of rectangular grooves.

Further, we analyze the FoM of the fundamental mode of the plasmonic waveguide for different quantities of the analyte. The FoM is defined by the ratio of sensitivity and full width at half maxima (FWHM) of the plasmonic mode. In calculating FoM, we first calculated FWHMs using transmittance values of the transmission output. In order to draw a comparative study, we have found the FoM results for the V grooves as well using the same methodology. In comparing FoM results, the analyte quantity was taken to be same for both the cases. The results are shown in Fig. 4 (b). The FoM values increases as the analyte quantity is increased within the grooves. The FoM of the fundamental plasmonic mode is observed to be much higher in case of V-grooves compared to the rectangular grooves. The higher values of sensitivity and FoM in case of V-grooves are believed to be due to the higher field confinement of the modes in V-grooves structures.

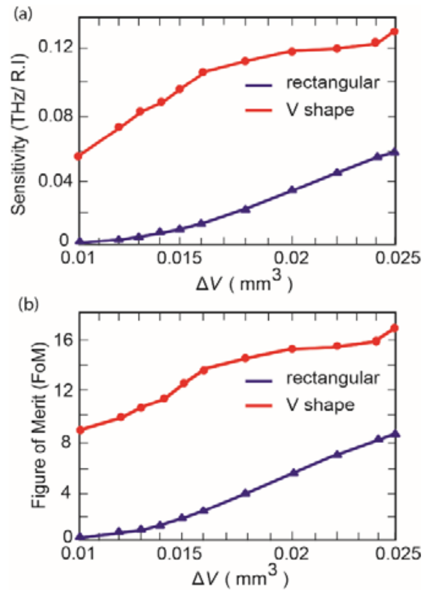

Fig. 4 Numerically calculated sensitivity and FoM of the fundamental mode of the plasmonic waveguides having V-grooves and rectangular grooves. (a) It represents the variation of sensitivity versus quantity of the analyte filling the grooves. In (b) the variation of the Figure of Merit is plotted versus the analyte quantity. The sensitivity and the FoM values are reported to higher in case of V-grooves

V. Conclusions

In conclusion, we have examined the capability of a planar plasmonic THz waveguide to sense an analyte. The rectangular dimples of the waveguide are filled with a polyimide substance of varying refractive index. We observe a linear shift in the anti-resonant frequency of the fundamental resonance mode with an increase in the refractive index of the analyte. In order to investigate sensing characteristics of the proposed waveguide, we calculated sensitivity and FoM of the fundamental mode with different quantities of the analyte. We found that as the quantity of the analyte is increased, both sensitivity and FoM increases. In an effort to improve sensing capability of the plasmonic waveguide, we examined sensing capability of the plasmonic waveguide comprising subwavelength scale V-grooves. For the same amount of analyte quantity ~ 0.025 mm^3, the sensitivity and FoM values for the waveguide with V-grooves are found to be ~ 0.13 THz / R.I and 16.75. However, for rectangular grooves the sensitivity and FoM turned out to be ~ 0.06 THz / R.I and 8.74, respectively. It indicates that the shape and size of the grooves and hence the electric field confinement to the surface are vital in determining the sensing capability of a plasmonic waveguide for the same quantity of material. The plasmonic waveguide for sensor applications could be significant in the construction of next generation high sensitive THz sensors.

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